# Corpuscular Streams Related to Solar M-regions*

by

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## ABSTRACT

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Recent studies on 27-day recurrence geomagnetic disturbances and their associated phenomena during the decline phase of the present sunspot cycle are summarized. An identification of M-region with solar phenomena has been made by evaluating the velocity of solar winds. Discussions are given on various existing hypotheses of corpuscular streams producing M-disturbances. *Author*

In order to provide a forum for discussion of the latest results on solar-geophysical disturbances during the period of quiet solar activity, a symposium on solar terrestrial relations was held on June 19, 1964, in Toyko. A number of formal presentations were given and they were accompanied by much stimulating discussion. Following are the major topics and contributors:

1. 27-day Recurrence Disturbances in Geophysics
   T. Saito, K. Nagashima, S. Mori, H. Ueno, and S. Sagisaka
2. On the Nature of Solar Winds
   Y. Sano, T. Ondho, Y. Hakura, and A. Nishida
3. Identification of the Solar M-region
   T. Goh, K. Sinno, S. Nagasawa, Y. Nakagomi, and Y. Nojima
4. Model of Solar Corpuscular Streams
   (discussion lead by T. Obayashi)

The present article constitutes a summarized report of the symposium, including some introductory remarks on the background of the present problem in solar terrestrial physics.

## 1. Introduction

The sun is the source of major disturbances in the terrestrial upper atmosphere through its radiative and corpuscular emissions. Solar corpuscular emissions consist of three types, viz., energetic solar particles and plasma clouds associated with solar flares, and the outward streaming of solar winds or beams of enhanced activity originating from the solar corona. The flare-associated solar particles have been investigated extensively during the past IGY and IGC, and their results were discussed elsewhere (Obayashi 1964). Meanwhile, successful launchings of deep space probes have lead to the discovery of the continual flow of solar plasmas with velocities of some hundreds km/sec (Neugebauer and Snyder 1962).

Renewed interest has arisen on the nature of recurrent geomagnetic disturbances with the solar rotation cycle, which had originally been suggested by Bartels many years ago as an enhanced stream of solar plasma ejected from some hypothetical active center of the sun, the so-called M-region. It has been known since the early part of this century that moderate geomagnetic disturbances show a tendency to recur at regular intervals of 27 days, particularly during periods of declining

sunspot activity. Numerous investigations[1] have been carried out to identify the active region of the sun responsible for such disturbances. Bartels (1932) first investigated the relation between recurrent geomagnetic disturbances and visible solar phenomena. No significant correlation was found. However, he noted that M-regions often occurred when the visible solar hemisphere was bare of sunspots or they tended to be absent when spots were near the central meridian of the sun. This feature was re-examined by Allen (1944) and he has concluded that sunspots tend to interfere with M-regions, or in other words, the M-region apparently shows a tendency to avoid spot areas, which is known as the cone of avoidance hypothesis. This interesting feature has been confirmed in the relation between coronal emission-line intensity and geomagnetic disturbances. The first suggestion of this line of investigation was made by Waldmeir (1942), who named the active coronal emission area as the C-region. Many investigators then showed that a significant minimum in geomagnetic acitvity follows 2-3 days after central meridain passage (cmp) of a region of active coronal emission, while two maxima in geomagnetic activity appear about 4-8 days after and also somewhat earlier than the time of the cmp of an acitve region (Shapley and Roberts 1946, Kiepenheuer

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[1] An extensive review has been given by Allen (1964).

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1947, Pecker and Roberts 1955, Notuki et al 1955, Sinno 1956, Bell and Galzer 1957, and Warwick 1959). Similar conclusions have also been obtained by the superposed epoch method, using solar flocculi data for a 35-year period (Saemundsson 1962).

In contrast to the concept of the cone of avoidance, Mustel (1961, 1962) advocated that M-regions appear to be correlated with active centers of the sun, possibly young plage regions, above which long coronal R-rays extend up to the distance of the earth's orbit. The coronal R-ray is believed to be a plasma stream, being composed of an assembly of radial magnetic field threads. There is another suggestion that M-regions are long-lived stable prominences, which are supposed to be remnants of old active regions.

In spite of these different hypotheses, all theories postulate solar active centers, and they admit that enhanced beams of solar corpuscles are the cause of recurrent geomagnetic disturbances. The important key to resolving the problem is, therefore, to determine the travel-time or the speed of streaming solar particles. Recent space probe data now provide this information. In their analysis of Mariner 2 plasma measurements, Snyder, Neugebauer and Rao (1963) have shown that a strong 27-day recurrence tendency exists in the daily time sequence of solar plasma velocity and concluded that the solar M-regions

must be the source of high velocity plasma. The average plasma velocity is nearly proportional to the geomagnetic activity or the daily sum of geomagnetic Kp indices. The estimated velocity of solar beams, thus derived from their results as well as the Explorer 18 data (Bridge et al 1964), ranges from 300 to 600 km/sec during the declining period of solar activity. This plasma velocity corresponds to the travel-time between the Sun and the earth of about 3 to 6 days, and the judgement of any theory must take into account this time-delay for solar-terrestrial relations.

There are some other phenomena which might be closely related to Solar M-regions. Cosmic ray variations, in particular, the diurnal anisotropy of the intensity, reveal a strong 27-day recurrence (Mori et al 1964). As will be shown, a significant correlation exists between the phase change of cosmic ray diurnal variations and the enhanced S-component of solar radio emissions. The activity index of geomagnetic micropulsations reveals a clear 27-day recurrence. Recent investigation shows that this new measure of geomagnetic activity may be very useful to study the M-region disturbances (Saito 1964). Since these phenomena are rather new and good data for the analysis are available only for the present cycle of the sunspot minimum, renewed studies on all related phenomena to solar M-regions during the present sunspot minimum will be discussed in what follows.

## 2. 27-day Recurrence Disturbances

In the present declining period of solar activity, some prominent recurrent geomagnetic disturbances have been observed. In Fig. 1, a 27-day recurrence pattern of the daily sum of geomagnetic planetary index $\Sigma$ Kp is shown for the period from August 1962 to December 1963. Throughout the whole period, a persistant major peak of activity appeared between the 5th to 10th days in 27-day rotation intervals. There were also short-lived minor peaks in the late half of the interval. Saito (1964) has found that the activity of pc3 geomagnetic pulsations reveals a very marked 27-day recurrence tendency in the same epoch. The daily cosmic ray intensity also showed a prolonged depression associated with the major peak of geomagnetic activity.

In order to compare geophysical disturbance phenomena with corresponding solar activity, the time series of coronal emission index G6 (5303 A) is shown in Fig. 2, in which values of east and west limbs of the northern hemisphere are used, the time being reduced to their cmp of the solar disk (Solar and Geophysical Data, CRPL-F, Part B, US-NBS). In general, two bright coronal regions appeared in each rotation cycle. In the present period of analysis, the feature of such double maxima of activity seems to be common for all other
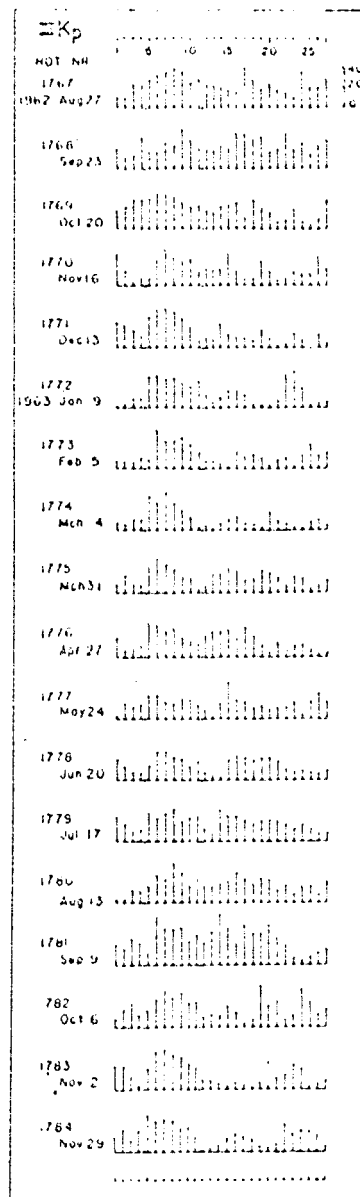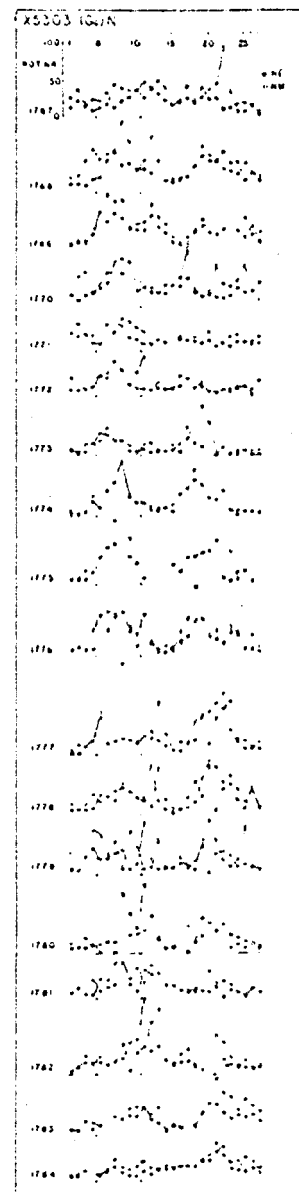
Fig. 1

Fig. 2

Fig. 1: 27-day recurrence pattern of geomagnetic planetary
indices Σ Kp from August 27, 1962 to December 25, 1963
(from Mori, Ueno, Nagashima and Sagisaka).

Fig. 2: 27-day recurrence pattern of coronal green line
indices G6 (5303) from August 27, 1962 to December
25, 1963. NE and NW: values at east and west limbs
on the northern solar hemisphere (from Mori, Ueno,
Nagashima and Sagisaka).

solar phenomena, such as sunspots, calcium-plages, and solar radio emissions (Nojima et al. 1964).

Average 27-day variations of these solar and geophysical phenomena during the period of most pronounced 27-day recurrency, between rotation numbers 1770 to 1776, a  illustrated in Fig. 3.  As has been stated, a major peak of geomagnetic activity dates from the 5th to 10th days, being followed by the decrease of cosmic ray intensity.  Coronal intensity and numbers of calcium-plages show double maxima, suggesting the existence of two stable centers of activity.  It has been shown that the slowly varying part, the S-component, of solar radio flux at microwave band recurs very regularly with peaks on the days of the 7th to 8th and near the 20th in each rotation cycle (Goh 1964, Mori et al. 1964).

There is another interesting phenomenon, recurring with the 27-day interval, viz., the amplitude and phase of the diurnal variation of cosmic ray intensity, the so-called DS-component of cosmic ray intensity.  Using data of meson monitor, Mori et al. (1964) obtained the average 27-day variation of cosmic ray diurnal vectors.  It has been found that significant phase advancements occur at the 6th and 22nd days, which have been known to appear during cosmic ray storms.  The
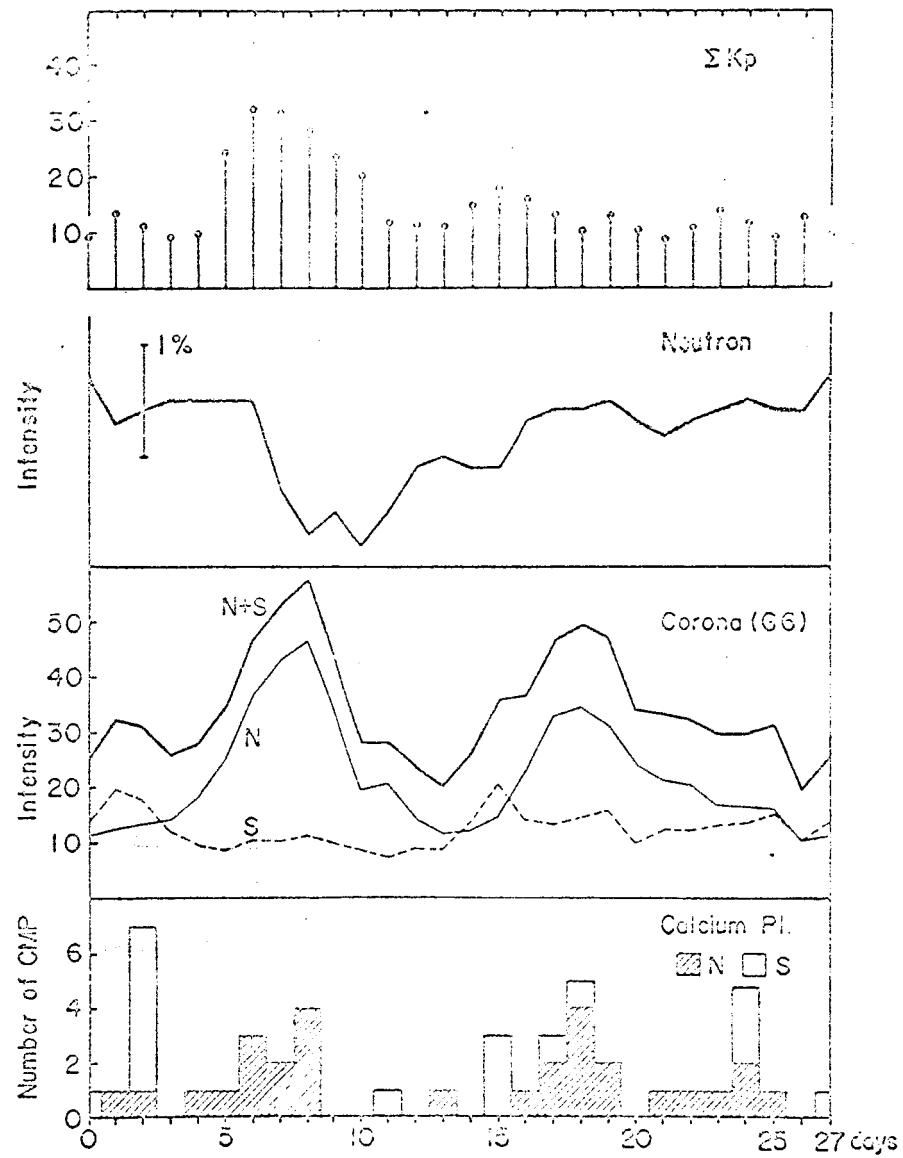
Fig. 3: Average 27-day variations of geomagnetic index
Σ Kp, cosmic ray intensity (climax), coronal green
line G6, and numbers of cmp of major calcium-plages
during the period from November 1962 to May 1963
(from Sinno).

27-day inequality of cosmic ray DS, the varying part of diurnal vectors with respect to the solar rotation, has been reduced, by subtracting the mean DS of the whole 27-day interval. With an appropriate phase correction for the geomagnetic effect, these residual DS flow vectors denoted by ΔDS, are obtained. They are illustrated by arrows in Fig. 4, on the heliocentric diagram together with average ΣKp and G6 variations. Although the physical mechanism causing the cosmic ray anisotropy has not been well understood, the ΔDS may indicate some additional flows, superposed upon the general modulation effect due to the outward streaming of solar winds.

## 3. Identification of Solar M-Regions

The general feature, illustrated in Fig. 4, is the observational basis for the identification of hypothetical solar M-regions, responsible for recurrent geophysical disturbances. It is important to note that the time of peaks of geomagnetic activity appears a few days ahead of the cmp of solar active centers. Since we believe that geomagnetic disturbances are produced by particle streams from the sun, these active centers cannot be satisfactorily identified as the sources for the immediately corresponding peaks of geomagnetic activity. Furthermore, it is now known that the
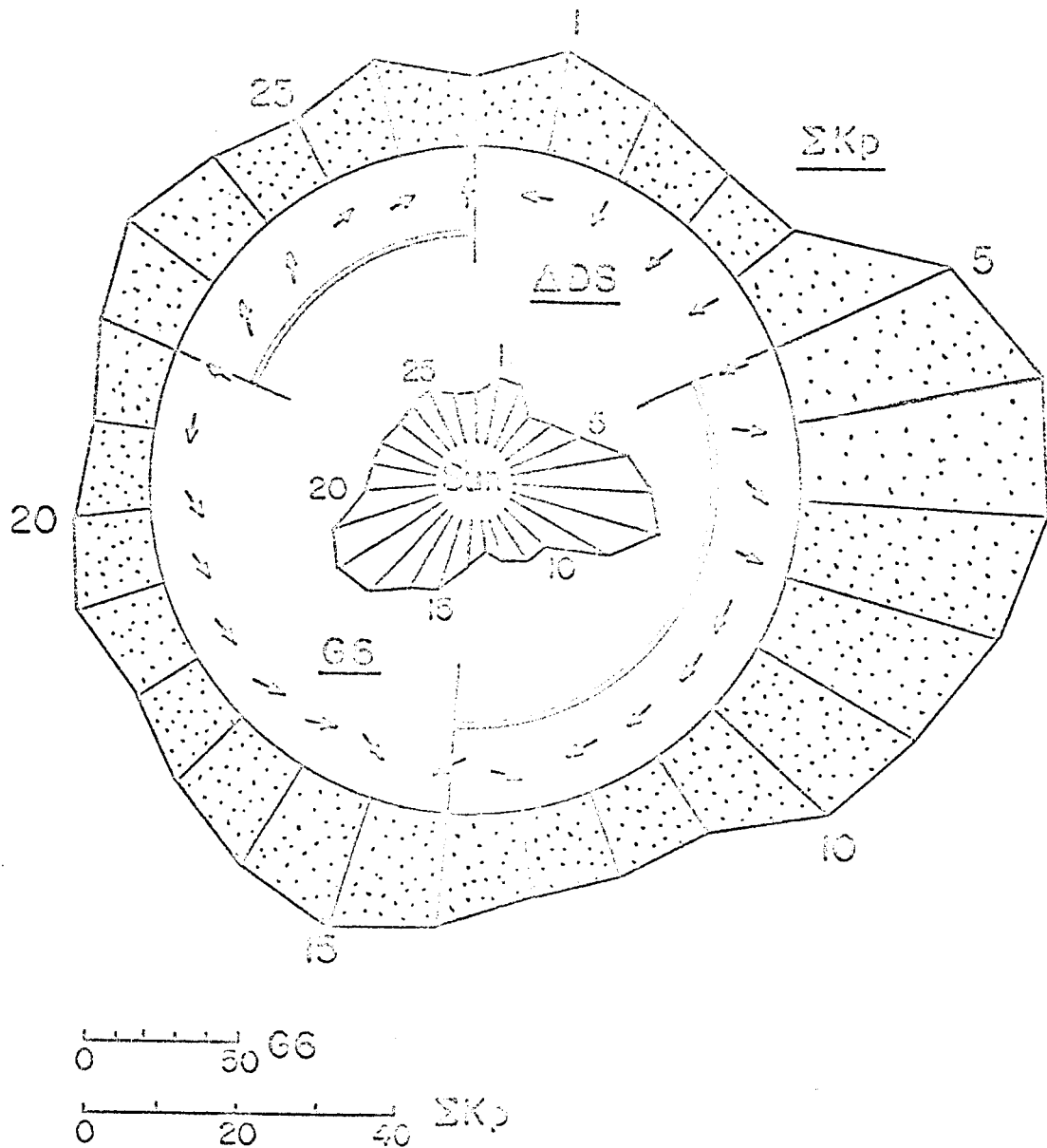
Fig. 4: Heliocentric diagram of 27-day variations of coronal
activity G6, cosmic ray Δ DS flow vectors and geomagnetic
index Σ Kp for the period of November 1962 to May 1963.

average velocity of plasma streaming out from the sun is about 400 - 600 km/sec, and these values yield the time-delay of the geophysical effect of 3 - 5 days.

To examine this point more quantitatively, the velocity of solar streams has been estimated from the value of $\Sigma$ Kp, by applying the Snyder's empirical relation between the solar wind velocity and $\Sigma$ Kp (Snyder, Neugebauer and Rao 1963). The delay-time computed from the estimated velocity is, then, used to shift the time of geophysical phenomena, so that they may be compared directly with positions of solar active centers. The result is shown in Fig. 5, in which the time of $\Sigma$ Kp and $\Delta$ DS is shifted approximately 3 - 5 days depending on their estimated stream velocities.

One of the features, which is immediately obvious, is that the major peaks of geomagnetic activity does not coincide with the center of coronal activity. The M-region should be located, if any, at the somewhat outer fringes of the active center, particularly, at the western side of the center. However, the situation is not so clear for other minor peaks of geomagnetic activity. A further discussion of the nature of solar M-regions is given later.

In earlier studies of the identification of solar

Average 27-Day Patterns During Rot. no. 1770-6
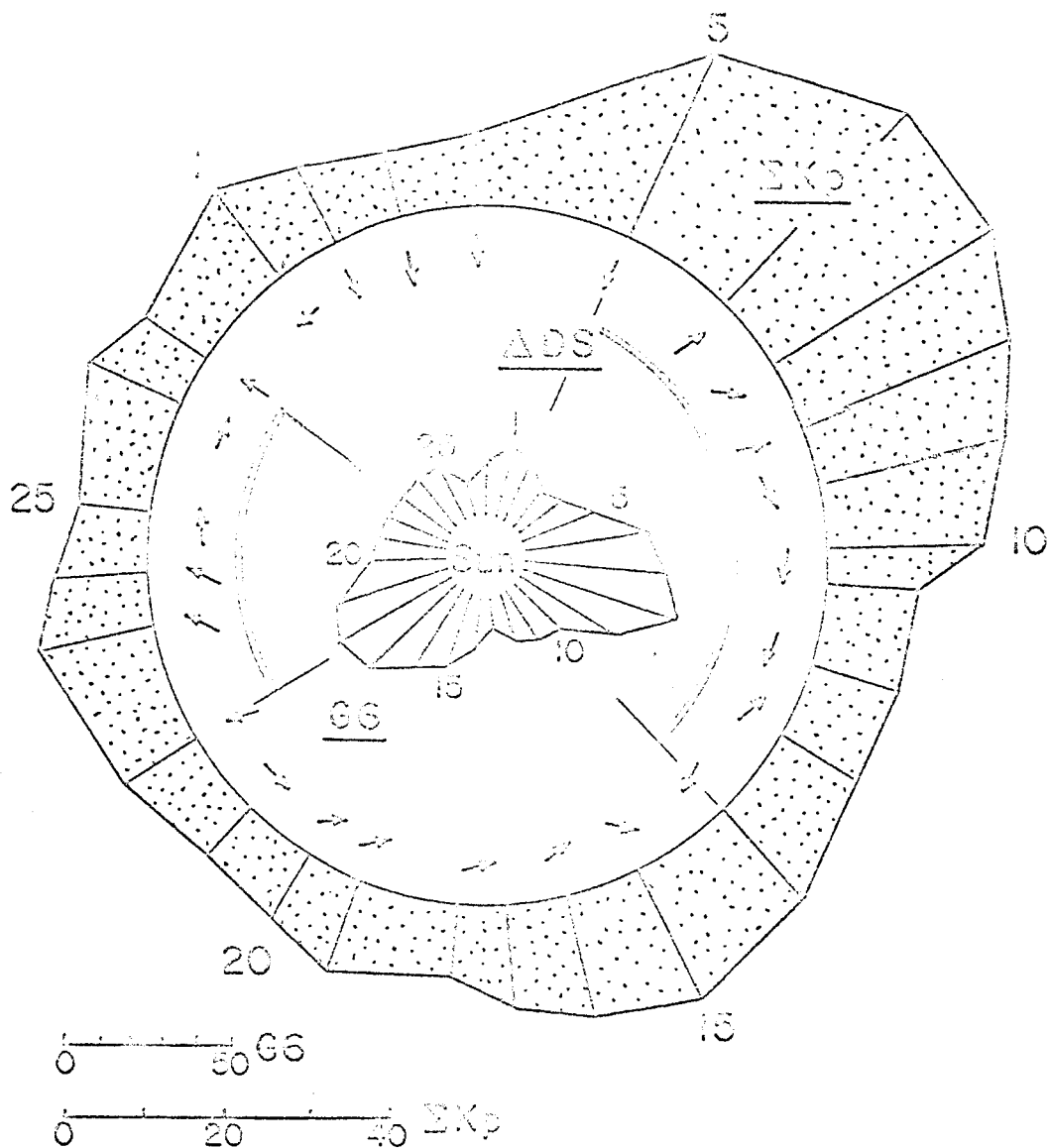(Corrected the Effect of Time Shift)



Fig. 5: Heliocentric diagram of 27-day variations of coronal activity G6, cosmic ray $\Delta$ DS and geomagnetic index $\Sigma$ Kp. The time series of $\Delta$ DS and $\Sigma$ Kp are shifted according to the time-delay of geophysical effects estimated from the solar stream velocities.

M-regions, most investig... ns employed the superposed epoch method. For the present period 1961 - 1963, Sinno (1964) made such an analysis and obtained the following result: Two sets of the superposed epoch graph of $\Sigma$ Kp for the cmp of bright and weak regions of solar corona, shown in Fig. 6, exhibit somewhat different features compared with those of previous sunspot cycles. However, the general tendency revealed in the graphs seems to agree with the hypothesis of the cone of avoidance, because a minimum of $\Sigma$ Kp appears 3 to 5 days after the cmp of bright corona, and a maximum of $\Sigma$ Kp appears 2 to 8 days after the cmp of weak corona. A similar conclusion has been obtained by Nojima et al. (1964) for the relation between active calcium-plages and geomagnetic activity. For the sake of comparison, superposed epoch graphs which have been obtained for the earlier sunspot cycles are reproduced in Fig. 7 (Bell and Glazer 1957, Warwick 1959). Since these analyses are statistical in nature, it is possible to have an apparent correlation between solar and geophysical activity even without any physical connection between them, provided that both of the time series have a 27-day periodicity. However, the similarity of patterns demonstrated here for the different epochs may be an important indicator of the likelihood that the above-mentioned relationship is real.
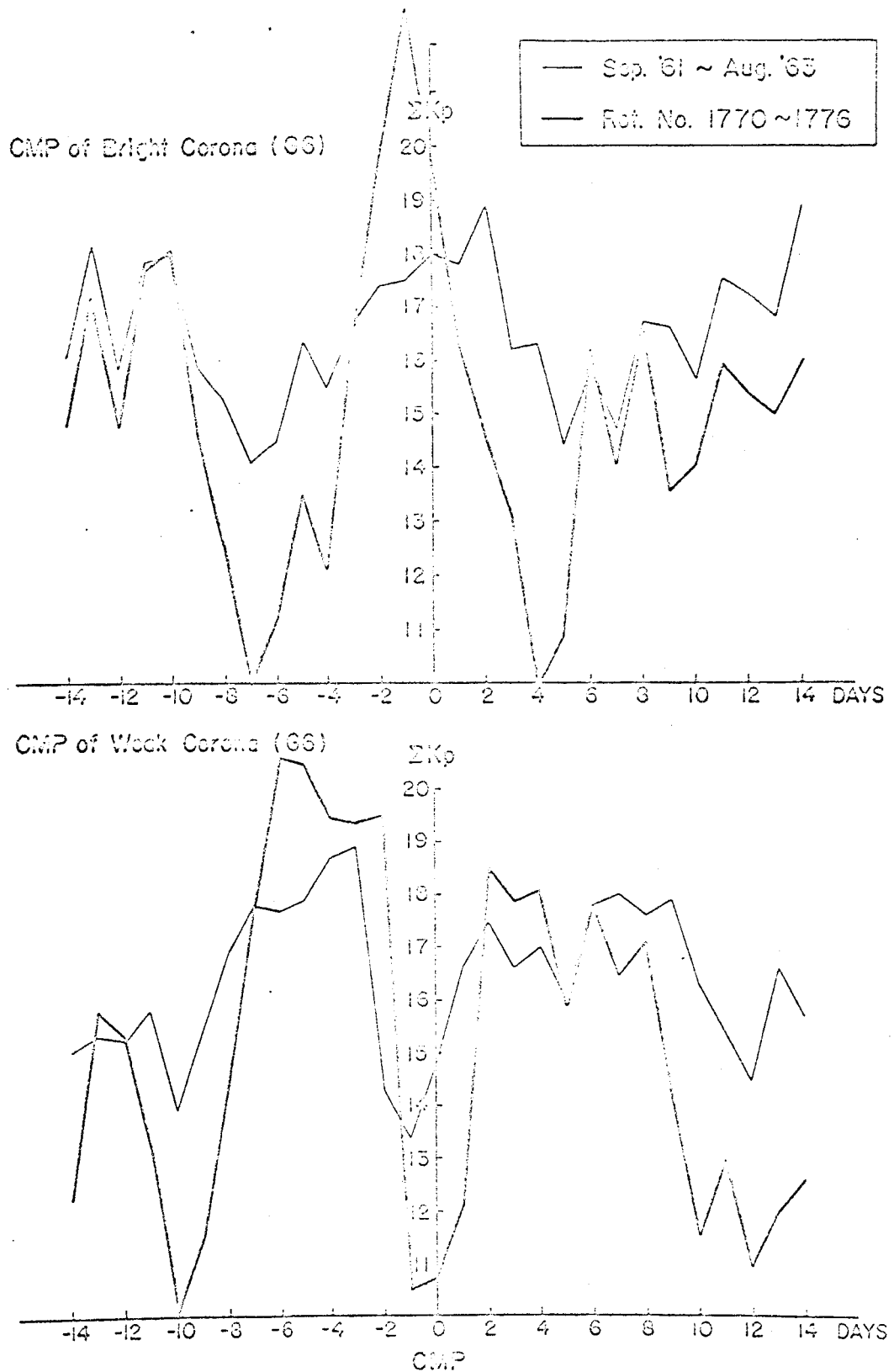
Fig. 6: Superposed epoch graphs of geomagnetic activity for the CMP of regions of bright and weak coronal intensities for the periods September 1961 to August 1963 and November 1962 to May 1963 (from Sinno).
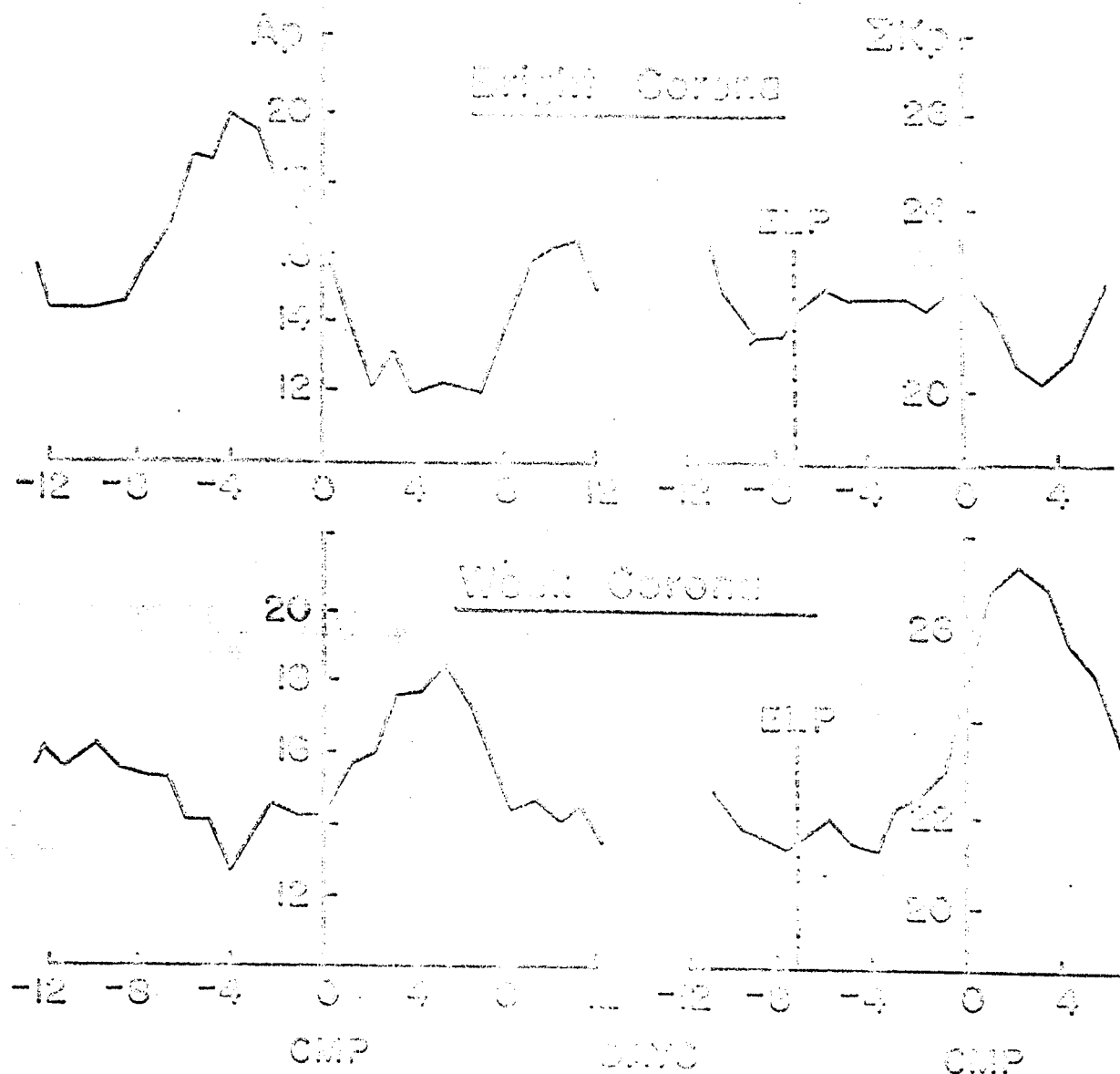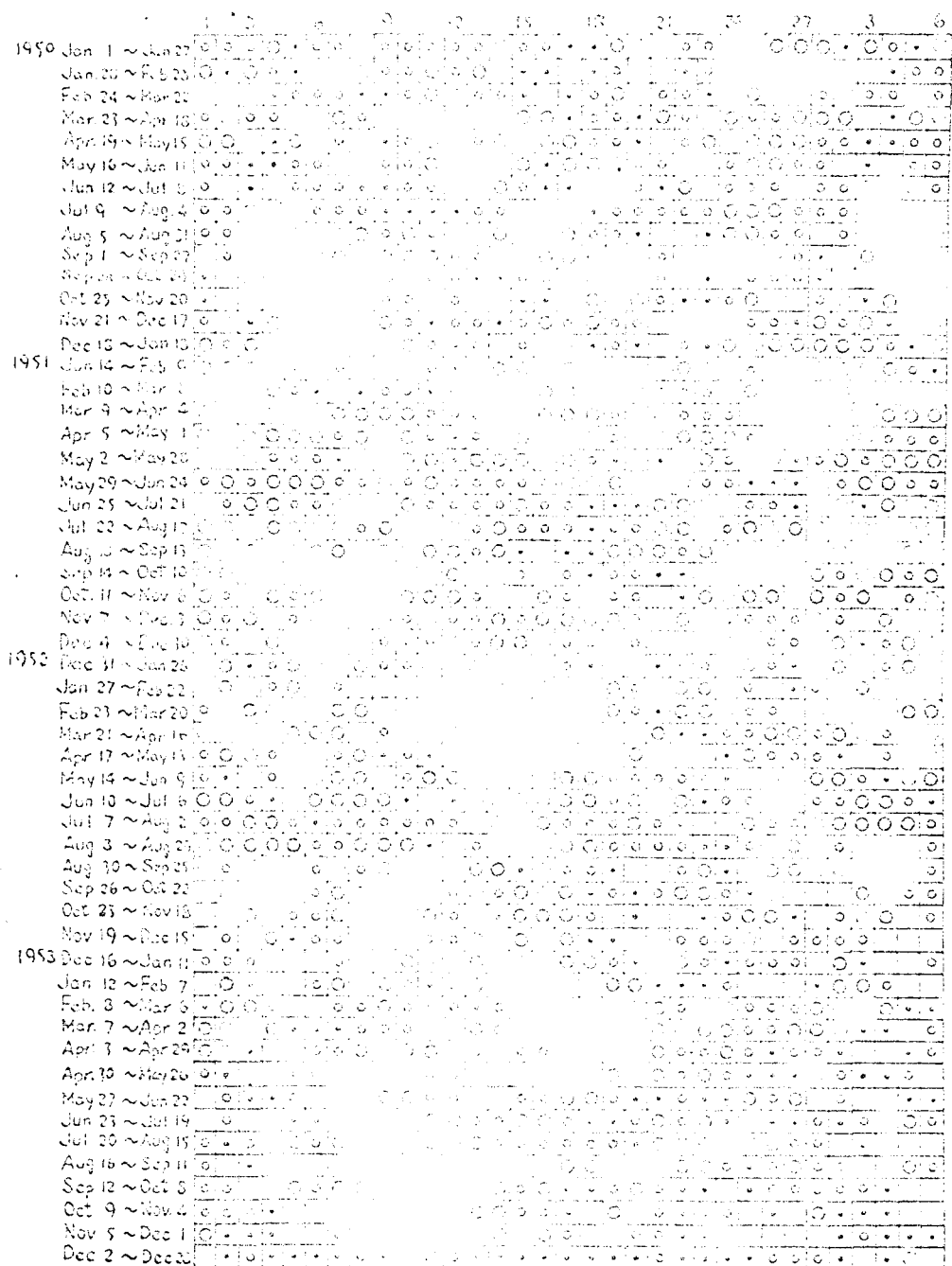
Bright Corona

Weak Corona

Fig. 7: Superposed epoch graphs of geomagnetic activity Ap
(or Σ Kp) after the CMP (or the eastern limb passage,
ELP) of bright and weak coronal regions, for the
periods 1942 - 1944 (Warwick) and 1950 - 1953 (Bell
and Glazer).

MAGNETIC ACTIVITY INTERNATIONAL CHARACTER-FIGURES

Fig. 8: 27-day recurrence pattern for geomagnetic character
figure, C-index for the period 1950 - 1953 (from
Sinno).

## 4. The Annual Effect of M-Regions

Since both recurrent geomagnetic disturbances and coronal active regions often persists for many solar rotation cycles, their long-term variations have been investigated by several workers. Sinno (1956) has pointed out two very long sequences of M-regions in the period 1950 - 1954, each of which appears to show an annual variation. As shown in Fig. 8, one long sequence located on the 3rd to 9th days of the rotation period showed a maximum activity around the autumnal equinox (September) and a minimum activity around the vernal equinox (March), which has been persisting for about three years or more. The other sequence appeared on the 12th to 18th days with its maximum around the vernal equinox. Such long-lived M-regions, being modulated by the annual period, have been found in the declining phase of every sunspot cycle (Tandon 1956).

The importance of this annual variation is that the beam from M-regions could be located not only on heliographic longitudes but also on latitudes, by taking into account the effect of the inclination of the solar axis to the plane of the ecliptic. It has been concluded by Bell and Glazer (1957) that the solar active region on the same side of the solar

equator as the earth have a greater influence on geomagnetic activity than do the active regions on the opposite side of the solar equator. In other words, the efficiency of an M-region in producing geomagnetic disturbances appears greatest when the earth is around its maximum favorable heliographic latitude, viz., the southern hemisphere in the vernal equinox and the northern hemisphere in the autumnal equinox, while it appears least when the earth is near its unfavorable (the opposite side of the equator) heliographic latitude.

From these observed facts of the directivity of solar streams from the M-region, Sinno (1956) has been able to deduce the beam width of streams to be of the order of $10^{\circ}$ in the solar meridian plane. This may be considerably narrower than the beam width in the equatorial plane, which is estimated to be of the order of $45^{\circ}$. Priester and Cattani (1962) found a similar beam width in the declining phases of sunspot cycle, from their analysis of the semiannual variation of geomagnetic activity.

5. Nature of Solar M-Regions

An important conclusion derived from statistical analyses is that recurrent geomagnetic disturbances are produced by corpuscular streams (hypothetical) originating not from the

center of solar activity but apparently from the outer fringes of the active area. According to the hypothesis of the cone of avoidance, an active center of the sun tends to inhibit the escape of corpuscles, and this is interpreted by assuming that solar particles are confined by strong local magnetic fields in the active center. In years of high solar activity, these trapped particles may be built up to form a strong condensation, being heated up further until they are finally exploded out. These are identified as solar flare corpuscles or flare-associated geomagnetic storms. In contrast to this explosive phase of solar activity, M-regions are such that the local magnetic fields are conducive to guide the continual outflow of corpuscular streams. This region may be compared to an unipolar magnetic region (Babcock and Babcock 1955) where the outward stream is strong enough so that the magnetic field lines will be stretched out in the direction of the stream.

Thus, the hypothesis of the cone of avoidance has an attractive feature for explaining the peculiar inhibition of the corpuscular beam emerging from the active center. Nevertheless, this hypothesis itself cannot offer any positive mechanism for ejecting narrow and strong corpuscular beams from M-regions. On the other hand, it has been established

that recurrent geomagnetic disturbances are closely related to the high velocity beam of solar winds (Snyder, Neugebauer and Rao 1963). According to Parker's theory (1960), the velocity of solar winds is very sensitive to the coronal temperature and, therefore, the solar corpuscular beam responsible for geomagnetic disturbances must originate from a high temperature region such as an active coronal condensation. As has been shown, however, this argument is not always consistent with observed results. Though Mustel's R-rays may be important for some recurring phenomena, they would possibly be remnants of solar flares, being dominated only during the stage immediately after the maximum solar activity (Bryant et al. 1963).

An alternative hypothesis for the cause of recurrent disturbances has recently been proposed by Dessler and Fejer (1963). Although they also postulate a high velocity beam streaming out from the active center, the origin of geomagnetic disturbances is attributed to a source other than the high velocity beam itself. It is emphasized that an enhanced solar stream alone cannot produce geomagnetic disturbances or high Kp, since the solar winds appear to be essentially ever-existing even during very quiet geomagnetic conditions. In these circumstances, they rejected the conventional view

of the cause of disturbances and proposed a hypothesis that

recurrent geomagnetic disturbances must be due to sheets of

turbulence or irregularities that are generated at the inter-

face of two solar wind regions of different stream velocities.

The high velocity solar stream will overtake the lower velocity

stream, and the collision of these streams would lead to the

Kelvin-Helmholtz instability or the formation of two shock

waves.  This mechanism predicts the region of disturbances

to lie westward of the high velocity beam originating from

the active center, which turns out to be very consistent with

the observed result shown in Fig. 5 for the period 1962 - 1963.

As has been pointed out by Piddington (1964) however, the

Dessler-Fejer theory does not appear satisfactory with the

result for the period 1950 - 1953, unless the stream velocity

above the active region would generally be lower than that of

the surrounding.  For this case the M-region lies eastward of

the active region of the corona, and he rather presumes that

main disturbances originate at the region of the following

side (eastward) of the high velocity beam, where the inter-

planetary field may be very weak or else lies in some favor-

able direction due to the sweeping action of a high velocity

stream ahead of the region.  A mechanism similar to this has

been suggested, independently, by Sarabhai (1963) as the source

of recurrent cosmic ray storms.

At present, since there is no sufficient direct observation of solar streams to locate the M-regions, the conclusion derived from statistical analyses alone is necessarily speculative, and it cannot be well justified to accept or reject any one of the hypotheses discussed here. It is hoped that extensive observations made during the IGSY will provide much useful material, stimulating new approaches to understanding the mechanism of the solar M-regions.

## Acknowledgement

# References

Allen, C. W., Relation between magnetic storms and solar
   activity, Mon. Not. Roy. Astr. Soc., 104, 13-21, 1944.

Allen, C. W., M-regions, Planet. Space. Sci., 12, 487-494, 1964.

Babcock, H. W. and Babcock, H. D., The sun's magnetic field,
   Astrophys. J. 121, 349-366, 1955.

Bartels, J., Terrestrial magnetic activity and its relation
   to solar phenomena, Terr. Mag. Atmos. Elect., 37,
   1 - 52, 1932.

Bell, B. and Glazer, H., Geomagnetism and the emission-line
   corona, 1950 - 1953, Smithsonian Contr. Astrophys., 2,
   51 - 107, 1957.

Bridge, H., Egidi, A., Lazarus, A., Lyon, E., and Jacobson, L.,
   Preliminary results of plasma measurements on IMP-A,
   Cospar Symposium, Florence, May 1964.

Bryant, D. A., Cline, T. L., Desai, U. D. and McDonald, F. B.,
   New evidence for long-lived solar streams in inter-
   planetary space, Phys. Rev. Letts., 11, 144 - 146, 1963.

Dessler, A. J. and Fejer, J. A., Interpretation of Kp index
   and M-region geomagnetic storms, Planet. Space Sci., 11,
   505 - 511, 1963.

Goh, T., The recurrence tendency of geomagnetic disturbances
and its association with the slowly varying component
of microwave solar radiation, Rep. Ionos. Space Res.
Japan, in the press, 1964.

Kiepenheuer, K. O., A slow corpuscular radiation from the
sun, Astrophys. J., 105, 408 - 423, 1947.

Mori, S., Ueno, H., Nagashima, K., and Sagisaka, S., The 27-
day recurrence tendency in cosmic ray intensity and
its correlation with solar and geomagnetic activity,
Rep. Ionos. Space Res. Japan, in the press, 1964.

Mustel', E. R., Results of a statistical study of geomagnetic
disturbances for 5 cycle of activity, Astro. Zh, 38,
28 - 44, 1961 (Soviet Astron. AJ., 5, 19 - 30, 1961).

Mustel', E. R., On the spatial structure of the solar corona,
Astro. Zh., 39, 619 - 631, 1962 (Soviet Astron. AJ.,
6, 488, 1963).

Neugebauer, M., and Snyder, C. W., Solar plasma experiment;
Preliminary Mariner 2 observation, Science, 138,
1095 - 1096, 1962.

Nojima, J., Nakagomi, Y., and Nagasawa, S., The relation
between the M-type magnetic disturbance and the solar
phenomena, Rep. Ionos. Space Res. Japan, in the press,
1964.

Notuki, M., Nakagomi, Y., and Fukatsu, M., Solar corona and
geomagnetism, Rep. Ionos. Res. Japan, 9, 215 - 221, 1955.

Obayashi, T., Streaming of solar particles between the sun
and the earth, Planet. Space Sci., 12, 463 - 485, 1964.

Parker, E. N., The hydrodynamic theory of solar corpuscular
radiation and stellar winds, Astrophys. J., 132, 821 - 866,
1960.

Pecker, J. C., and Roberts, W. O., Solar corpuscles responsible
for geomagnetic disturbances, J. Geophys. Res., 60,
33 - 44, 1955.

Piddington, J. H., Recurrent geomagnetic storms, solar M-
regions and the solar wind, Planet. Space Sci., 12,
113 - 118, 1964.

Priester, W., and Cattani, D., On the semiannual variation
of geomagnetic activity and its relation to the solar
corpuscular radiation, J. Atmos. Sci., 19, 121 - 126,
1962.

Saemundsson, Th., Statistics of geomagnetic storms, Mon. Not.
Roy. Astr. Soc., 123, 299 - 316, 1962.

Saito, T., An index of geomagnetic pulsation fo_ detecting
solar M-region, Rep. Ionos. Space Res. Japan, in the
press, 1964.

Sarabhai, V., Some consequences of non-uniformity of solar
wind velocity, J. Geophys. Res., 68, 1555 - 1557, 1963.

Shapley, A., and Roberts, W. O., The correlation of magnetic disturbances with intense emission regions of the solar corona, Astrophys. J., 103, 257 - 274, 1946.

Sinno. K., On the origin of the long-lived solar corpuscular streams which appeared last solar cycle, 1950 - 53, Rep. Ionos. Res. Japan, 10, 250 - 260, 1956.

Sinno, K., On the study of M-regions during 1961 to 1963, Rep. Ionos. Space Res. Japan, in the press, 1964.

Snyder, C. W., Neugebauer, M., and Rao, U.R., The solar wind velocity and its correlation with cosmic ray variations and with solar and geomagnetic activity, J. Geophys. Res., 68, 6361 - 6370, 1963.

Tandon, J. N., A note on the annual variation of geomagnetic activity, J. Geophys. Res., 61, 211 - 213, 1956.

Waldmeier, M., Koronaintensität und Erdmagnetismus, Zeitschr. Astrophys., 21, 275 - , 1942.

Warwick, C., Green coronal line intensity and geomagnetism, J. Geophys. Res., 64, 527 - 531, 1959.